

# SN 2011ht: WEAK EXPLOSION IN MASSIVE EXTENDED ENVELOPE

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## Abstract

A possibility is explored to account for the light curve and the low expansion velocity of the supernova SN 2011ht, a member of group of three objects showing signatures of both IIn and IIP supernovae. It is argued that the radiated energy and the expansion velocity are consistent with the low energy explosion ( $\approx 6 \times 10^{49}$  erg) and  $\leq 2 M_{\odot}$  ejecta interacting with the circumstellar envelope of  $6 - 8 M_{\odot}$  and the radius of  $\sim 2 \times 10^{14}$  cm. The test of this scenario is proposed.

## 1 Introduction

Among type IIn supernovae (SN IIn, with "n" standing for "narrow lines") that are commonly associated with the presence of a dense circumstellar medium there is a unique variety composed of SN 1994W (Sollerman et al. 1998), SN 2009kn (Kankare et al. 2012), and SN 2011ht (Roming et al. 2012; Mauerhan et al. 2013). Their bolometric light curve has  $\sim 120$  days plateau reminiscent of SN IIP. The plateau ends up with the luminosity drop by a factor of ten and a subsequent exit to the tail somewhat similar to the radioactive tail of SN IIP but probably of different origin. Maximum with  $\sim -18$  mag is attained at about day 40. The spectrum is smooth continuum with strong emission lines of  $H\alpha$  and  $H\beta$  characterized by the narrow core (FWHM  $\sim 700 - 800$  km s $^{-1}$ ) and broad wings  $\sim \pm 5000$  km s $^{-1}$ . Apart from hydrogen lines the spectrum shows narrow metal lines, mostly Fe II, with velocity of absorption minima of  $\sim -(500... 700)$  km s $^{-1}$ . The similarity of light curves and spectra of the mentioned supernovae justifies their selection into a special group designated SN IIn-P (Mauerhan et al. 2013); the notation emphasises their resemblance with SN IIn and SN IIP first mentioned for SN 1994W (Sollerman et al. 1998).

The model of SN 1994W proposed earlier suggested the explosion of the red supergiant with  $7 M_{\odot}$  ejecta and the kinetic energy of  $\sim 10^{51}$  erg (Chugai et al. 2004). According to this scenario (dubbed as scenario A) the supernova interacts with the dense extended circumstellar (CS) envelope; narrow lines form in the CS envelope expanded at  $\sim 10^3$  km s $^{-1}$ ; broad wings are

produced by the scattering of line photons on thermal electrons of the same CS envelope. This scenario, however, faces a serious problem, because it is becoming clear that at the late stage ( $t > 120$  d) supernovae SN IIn-P do not show signatures of the high-velocity material ( $\sim 4000$  km s $^{-1}$ ) that is predicted by this scenario. One might suggest that this gas is not seen because the cool dense shell (CDS) at the contact surface between supernova and CS material is very opaque. At the late stage this situation might occur, if the dust forms in the CDS. Yet the case of SN 1998S where the dust indeed seem to form in the CDS (Pozzo et al. 2004) broad emission lines are seen, possibly because of the mixing of the fragments of the CDS with the hot gas of the forward shock.

In the alternative scenario (call it B) proposed by Dessart et al. (2009) the spectrum of SN 1994W, including the continuum and lines, forms in a massive envelope with low expansion velocity ( $\sim 1000$  km s $^{-1}$ ) implied by narrow lines. In fact, authors have demonstrated that the expanding atmosphere with a steep density gradient, the effective temperature of  $\sim 7000$  K, and photosphere radius of  $\sim 10^{15}$  cm reproduces the observed spectrum fairly well. The success of the straightforward scenario in the modelling of the non-trivial spectrum makes this scenario very attractive. Noteworthy, the scenario B does not contain high velocity gas unlike the scenario A.

The scenario B, however, leaves open a question, whether the energy requirements are consistent with the low expansion velocity. The present paper is focused on this issue. To this end a model is developed to describe the phenomenon of SN 2011ht for which most complete observations are available compared to other two SN IIn-P. The model is based on the thin shell approximation that is commonly used for the analysis of SN IIn. Here, however, the model includes diffusion of the trapped radiation in the optically thick envelope. The section 2 describes the model, while the section 3 presents results of the light curve modelling. The modelling of line profiles of H $\alpha$  and H $\gamma$  is presented in section 4. Note, the simultaneous description of these lines in the framework of the unified model of the emission and Thomson scattering in CS envelope turned out problematic in the former scenario of SN 1994W (Chugai et al. 2004).

The discovery on 2011 September 29 (JD=2455834) caught SN 2011ht during the rapid flux rise (Roming et al. 2012; Mauerhan et al. 2013). It is reasonable to admit, therefore, that the explosion took place a few days before the discovery. Here the explosion date JD=2455830 is adopted.

## 2 General considerations and model

The velocity at the photosphere of SN 2011ht fixed by absorption minima, e.g., H $\alpha$  is about 600 km s $^{-1}$  (Mauerhan et al. 2013); this value remains constant through the spectral observations ( $t > 30$  d) at the plateau stage. The latter indicates that the velocity dispersion and the relative thickness of the shell are rather small. Furthermore, the velocity persistence also suggests

**Table:** Parameters of SN 2011ht models

Model	$E$ $10^{50}$ erg	$M_{sn}$ $M_{\odot}$	$M_{cs}$ $M_{\odot}$	$R_{cs}$ $10^{14}$ cm	s	$E_r$ $10^{50}$ erg
m1	0.6	0.01	10	2	0	1.9
m2	0.6	2	8	2	0	1.5
m3	0.57	2	6.5	2.5	0	1.7
m3f	0.57	2	6.5	2.5	0	2.5
m4	0.6	2	7	3.5	2	2.0
m4f	0.6	2	7	3.5	2	3.0

that the shell acceleration phase is brief,  $t_a \leq 30$  d, which means in turn that the external radius of the CS envelope is  $R_{cs} \sim vt_a \leq 2 \times 10^{14}$  cm. The main stage of the radiative cooling ( $\sim 120$  d) therefore should be considered as the result of slow diffusion of the trapped radiation generated at the early phase  $t \leq 30$  d. In this respect SN 2011ht is similar to SN IIP. The difference is that the bulk of SN IIP matter is distributed in a wide range of velocities which is manifested in the significant decrease of the photospheric velocity at the plateau in contrast to SN IIn-P. The diffusion time characterized by the plateau stage is several times greater than the acceleration time, so a significant fraction of the internal energy is spent on the pressure work at the plateau stage. The strong radiation-dominated shock in the uniform medium deposits 80% of the energy in the internal energy (i.e., radiation) and 20% in the kinetic energy (Chevalier 1976). Assuming that the initial internal energy is equally shared between the work on the expansion and the escaped radiation, we conclude that roughly 2/3 of the explosion energy is spent on the kinetic energy of the accelerated shell, while 1/3 is escaped radiation. Given the radiated energy of SN 2011ht of  $\approx 2 \times 10^{49}$  erg (Mauerhan et al. 2013) we thus conclude that the kinetic energy is  $\sim 4 \times 10^{49}$  erg and the explosion energy is  $E \sim 6 \times 10^{49}$  erg. Taking into account the expansion velocity of  $v \approx 600$  km s $^{-1}$  and the estimated kinetic energy we infer the total mass of the expanding shell as  $M \sim 10 M_{\odot}$ .

The small relative thickness of the shell and the brief acceleration phase prompts us a simple model based on the thin shell approximation (Giuliani 1982). We consider geometrically thin, but optically thick, shell with the interior filled by the radiation. The radiation energy is determined by the dissipation of the kinetic energy of the supernova ejecta, by the work of the radiation pressure, and the radiation escape via diffusion. The equation of motion for this shell is (cf. Giuliani 1982)

$$M \frac{dv}{dt} = 4\pi R^2 \left[ \rho_{sn} \left( \frac{R}{t} - v \right)^2 + p - \rho_{cs} v^2 \right], \quad (1)$$

where  $M$  is the mass of the shell with the radius  $R$ ,  $v$  is the shell expansion velocity,  $\rho_{sn}$  is the supernova density at the radius  $R$ ,  $\rho_{cs}$  is the CS density at

the radius  $R$ , and  $p$  is the radiation pressure that is assumed to be uniform in the cavity. The expansion velocity of undisturbed CS matter is presumably negligibly small. Undisturbed supernova ejecta are assumed to expand homologously, ( $v = r/t$ ) with the density distribution  $\rho \propto (v_0/v)/(1 + (v/v_0)^7)$ , i.e.,  $\rho \propto v^{-1}$  in the inner zone ( $v < v_0$ ) and  $\propto v^{-8}$  in the outer layers.

The radiation pressure in the cavity is  $p = E_r/(4\pi R^3)$ , where  $E_r$  is the radiation energy described by the equation

$$\frac{dE_r}{dt} = 2\pi R^2 \rho_{sn} \left( \frac{R}{t} - v \right)^3 - E_r \frac{v}{R} - \frac{E_r}{t_c}. \quad (2)$$

The first term in the right hand side is the rate of the internal energy generation due to the ejecta collision with the thin shell, the second term is the work of the radiation pressure, and the last term is the luminosity due to the radiation diffusion. The luminosity is determined as  $L = E_r/t_d$ , where the diffusion time is

$$t_d = \xi \frac{R}{c} \tau. \quad (3)$$

Here  $\tau \gg 1$  is the shell optical depth,  $c$  is the speed of light, and  $\xi$  is a factor of order unity related to the geometry. For the central source in the uniform sphere  $\xi = 0.5$  (Sunyaev and Titarchuk 1980); a similar value one obtains for the geometrically thin shell filled by the isotropic radiation. We adopt  $\xi = 0.5$ .

The shell optical depth is calculated using Rosseland opacity (Alexander 1975). The temperature distribution in the shell is determined iteratively on the bases of the Eddington solution for the plane slab,  $T^4 = (3/4)T_e^4(2/3 + \tau)$ , where  $T_e$  is the effective temperature. The shell density is assumed to be equal  $\rho_s = 7\rho_{cs}$  in line with the density jump in the strong radiation-dominated shock. After the shock break out of the CS envelope ( $R > R_{cs}$ ) the shell density is set to be  $\rho_s \propto (R_{cs}/R)^3$  implied by the free expansion. The system of equations of motion, energy, and mass conservation is solved by Runge-Kutta of 4-th order. In every case the energy is conserved with the accuracy of 1%.

To test the model we calculated the result of a central explosive release of  $10^{51}$  erg in the uniform envelope of  $4.2 M_\odot$  and the radius of  $5 \times 10^{13}$  cm. The explosion is simulated by the kinetic energy of  $0.01 M_\odot$  shell. In this formulation the modelling in the framework of the radiation hydrodynamic is available (Chevalier 1976, model A). The light curve in our model slightly differs from that of the model A but the length of the plateau in both models (57 days) coincide within one day. Despite its simplicity our model thus catches the essence of the acceleration dynamics and the light curve produced by the explosion in an extended envelope.

### 3 Modelling results

SN 2011ht parameter estimates recovered above are used here for two illustrative models, m1 and m2 (cf. Table and Fig.1). The Table contains the

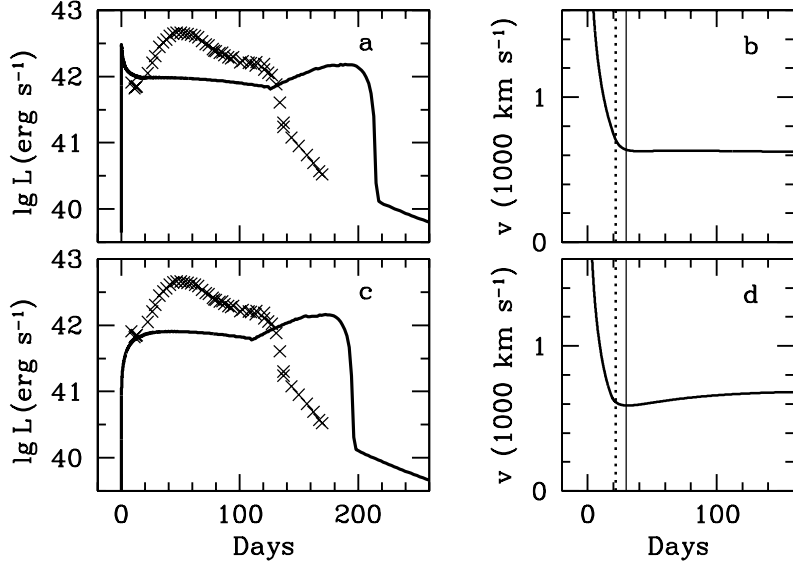


Figure 1: Model bolometric light curve (panels *a* and *c*), compared to observations of SN 2011ht (*crosses*, Mauerhan et al. 2013; Roming et al. 2012), and the model thin shell velocity (panels *b* and *d*). Model m1 (cf. Table) is plotted in panels *a* and *b*, model m2 is in panels *c* and *d*. The vertical *solid* line in panels *b* and *d* corresponds to the epoch of the first spectrum (day 30), while the *dotted* line shows the moment when the thin shell radius is equal to  $R_{cs}$ .

explosion energy and mass of SN ejecta, the mass of the CS envelope, its radius  $R_{cs}$ , the power index  $s$  of the density distribution,  $\rho \propto r^{-s}$ , in the range of  $r < R_{cs}$ , and the radiated energy. In both models  $s = 0$  while  $\rho \propto r^{-6}$  for  $r > R_{cs}$ . The model m1 with the ejecta mass of  $0.01 M_{\odot}$  in fact simulates the central explosion since the kinetic energy of the low mass ejecta is rapidly ( $t < 1$  d) thermalized. The aggregated mass of the supernova ejecta and CS envelope is  $10 M_{\odot}$  in both models. The models sensibly reproduce the total radiated energy (cf. Table) and the observed expansion velocity of SN 2011ht after day 30. Both models however have apparent drawbacks: the plateau is unacceptably long and the shape of the light curve is unlike the observed one. Particularly, the model does not show the hump at about day 50. Note, the late hump of the model light curve at the plateau end is related to the sharp drop of the opacity with the temperature decrease around  $10^4$  K.

The comparison of our simplified model with hydrodynamic simulation in the previous section suggests that the strong disagreement between the model and observed plateau duration is unlikely, although cannot be ruled

out completely. The problem with the light curve description might arise because some relevant physics is not included in our model. We admit that the missing factor is the fragmentation of the swept-up shell as a result of either the Rayleigh-Taylor instability arising from the rapid deceleration of the shell (Fig.1), or the thin shell instability in the case of the radiative forward shock (Vishniac 1983). The outcome of the fragmentation is the decrease of the shell effective optical depth and, as a result, rapid radiation diffusion and larger luminosity at the early epoch.

The fragmentation effect in the light curve can be implemented using the following description. A homogeneous spherical layer with the optical depth  $\tau$  breaks down into spherical fragments of a radius  $a$  with  $N$  to be the number density of fragments. The gas density in fragments is assumed to be the same as in the smooth shell, while the intercloud density to be negligibly small. The average number of clouds along the shell radius is then  $\tau_{oc} = \pi a^2 N \Delta r$ , where  $\Delta r$  is the shell thickness. Using  $\tau_{oc}$  one can write the expression for the effective optical depth of the cloudy shell (cf. Chugai & Chevalier 2005) as

$$\tau_{eff} = \tau_{oc}[1 - \exp(-\tau/\tau_{oc})]. \quad (4)$$

This expression deviates from the exact one (Utrobin & Chugai 2015) by less than 3%. In the limit of  $\tau_{oc} \gg \tau$  the relation (4) reproduces the optical depth of the smooth shell,  $\tau_{eff} = \tau$ , while for  $\tau_{oc} \ll \tau$  the effective optical depth is reduced to average number of clouds along the shell radius,  $\tau_{eff} = \tau_{oc}$ . The fragmentation evolution is described via the time dependence of  $\tau_{oc}$

$$\tau_{oc} = \tau_{oc,2} + \tau_{oc,1}/[1 + (t/t_f)^6]. \quad (5)$$

The value of  $\tau_{oc,1}$  is set to meet the requirement  $\tau_{oc,1} \gg \tau_0$ , where  $\tau_0$  is the initial optical depth of the smooth shell. We assume  $\tau_{oc,1} = 5\tau_0$  and  $\tau_{oc,2} = 200$ : the choice guarantees that at the early epoch  $\tau_{eff}$  is equal to the optical depth of the smooth shell. This description suggests that the fragmentation becomes significant at the stage  $t \geq t_f$ .

The fragmentation effect in the light curve is demonstrated by models m3f and m4f (Table, Fig.2) in comparison with models m3 and m4 without fragmentation. Models m3f and m4f differ by the initial density distribution of the CS envelope: in the model m3f the density is uniform ( $s = 0$ ), while in the model m4f  $s = 2$ . The fragmentation time is  $t_f = 13$  d in the model m3f and 10 days in the model m4f. Model light curves describe better principal features of the observed light curve: maximum at about day 50 and the plateau duration. The shell expansion velocity in both models is close to  $600 \text{ km s}^{-1}$ , in accord with observations. Note that the velocity exit on the constant regime in the model m4f occurs later than both in the model m3f and observations; we therefore conclude that the model m3f is preferred. Exercises with different ejecta mass confirm an obvious guess: a model with larger mass exits to the constant velocity later because of the larger momentum. The model m3f exits to the constant velocity at about day 30, and thus demonstrates that the ejecta mass cannot exceed significantly  $2 M_\odot$ . At the

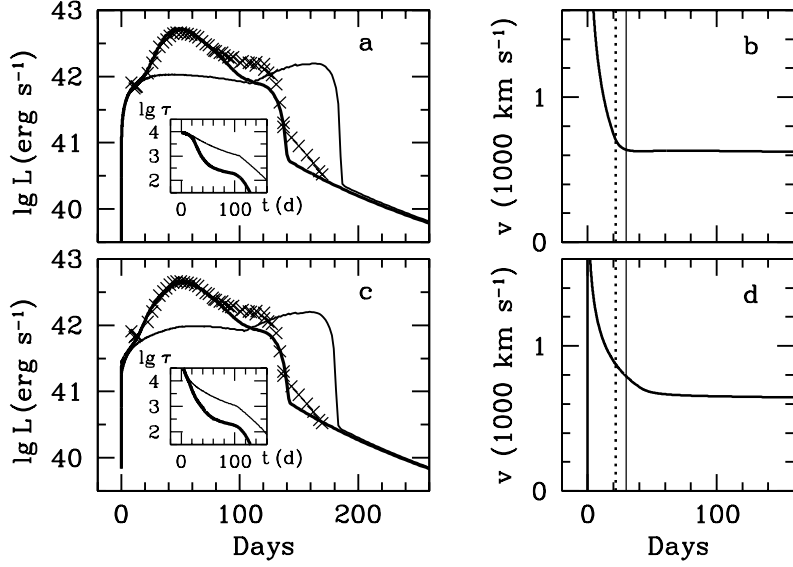


Figure 2: The same as Fig.1, but for models with the fragmentation (m3f and m4f, cf. Table). *Thin* line shows the model without fragmentation. *Insets* in panels *a* and *c* show evolution of the Rosseland optical depth in the model without fragmentation (*thin* line) and with fragmentation.

luminosity maximum ( $\approx 50$  d) the effective temperature in the model m3f is  $10^4$  K in agreement with the temperature inferred from the spectral energy distribution (Mauerhan et al. 2013). This additionally lends credibility that the model reflects basic physics of SN 2011ht phenomenon.

For the model verification of great interest is the early stage  $t < t_a$  that precedes complete sweeping of the CS envelope, i.e., when the thin shell radius  $R < R_{cs}$ . In the model m3f this stage corresponds to  $t < t_a = 21.6$  d (Fig.2). Our scenario predicts that at  $t < t_a$  the photosphere radius is constant and equal to  $R_{cs}$ , while the velocity at the photosphere should coincide with the velocity of the undisturbed CS envelope, which is presumably small. We expect in this case that the spectrum at  $t < t_a$  with the resolution  $> 100$  km s $^{-1}$  will not reveal absorption lines, while core of emission hydrogen lines will be narrower than at the late time,  $t > t_a$ .

Summing up, the radiated energy and the low expansion velocity of SN 2011ht are consistent with the explosion of supernova of low energy ( $\approx 6 \times 10^{49}$  erg) in the CS envelope of the radius  $\sim 2 \times 10^{14}$  cm with the total mass of the swept-up shell of  $\approx 8 - 9 M_{\odot}$ .

## 4 Hydrogen line profiles

In the proposed scenario the shock wave sweeps up the CS envelope in the initial 20-30 days. After that the shell expands freely with the velocity of  $\approx 600 \text{ km s}^{-1}$  and kinematics of  $v = r/t$ . The hydrogen line emission produced by the shell with the large Thomson optical depth, and the hydrogen absorption arising from the external rarefied layer can provide us with an additional test of the SN 2011ht model. The Monte Carlo technique is used below to model hydrogen line profiles.

Compared to the similar modelling of  $\text{H}\alpha$  formed in the cocoon of SN 1998S with the Thomson optical depth of  $\tau_T \approx 3$  (Chugai 2001), in the case of SN 2011ht the optical depth of the emitting shell is tremendous ( $\tau_T > 10^2$ ), so one has to take into account the true absorption of quanta between scatterings. This process is modelled by introducing the absorption probability  $p = k_a/(k_a + k_T)$ , where  $k_a$  and  $k_T$  are the coefficients of absorption and Thomson scattering respectively. It is assumed that the shell consists of two components: optically thick ( $\tau_T > 10^2$ ) spherical layer in the velocity range of  $v_1 < v < v_2$  and the optically thin ( $\tau_T = 0.5$ ) external layer in the velocity range  $v_2 < v < v_3$  responsible for the absorption component. The ratio of line and continuum emission coefficients is assumed to be constant in the envelope; the electron temperature is set to be  $10^4 \text{ K}$ .

As an example we consider the spectrum of SN 2011ht on day 37 (Mauerhan et al. 2013). According to the model m3f at this stage the shell optical depth is  $\tau_T \approx 10^3$ . We adopt  $\tau_T = 10^3$  and note that the variation of this value in the range of factor three does not affect the result significantly. The resonance optical depth in lines is assumed to be very large in the range of  $v_1 < v < v_3$ . Computations of the  $\text{H}\alpha$  profile for the extended set of parameters led us to the optimal choice  $v_1 = 550 \text{ km s}^{-1}$ ,  $v_2 = 650 \text{ km s}^{-1}$ ,  $v_3 = 850 \text{ km s}^{-1}$ , and  $p = 0.09$  (Fig.3). To model  $\text{H}\gamma$  one has to take into account that the absorption probability should be smaller than in the  $\text{H}\alpha$  band because the absorption is determined primarily by the Paschen continuum. If one takes into account only this absorption mechanism then for the  $\text{H}\gamma$  band one gets  $p = 0.026$ . However, the  $\text{H}\gamma$  calculated with this value shows very strong broad wings due to large number of scatterings on thermal electrons. The best agreement with the observed spectrum is found for  $p = 0.054$ . The absorption coefficient is larger than the Paschen value possibly because of the contribution of numerous metal lines in this band. With the correction for the uncertainty of  $p$  for  $\text{H}\gamma$ , we find that both  $\text{H}\alpha$  and  $\text{H}\gamma$  are well described by the unified model of the SN 2011ht consistent with the light curve model as regards principal parameters (velocity, temperature, and optical depth). This success demonstrates advantage of the scenario B over scenario A: in the latter  $\text{H}\gamma$  profile could not be reproduced solely by the emission and scattering in the undisturbed CS envelope (Chugai et al. 2004).



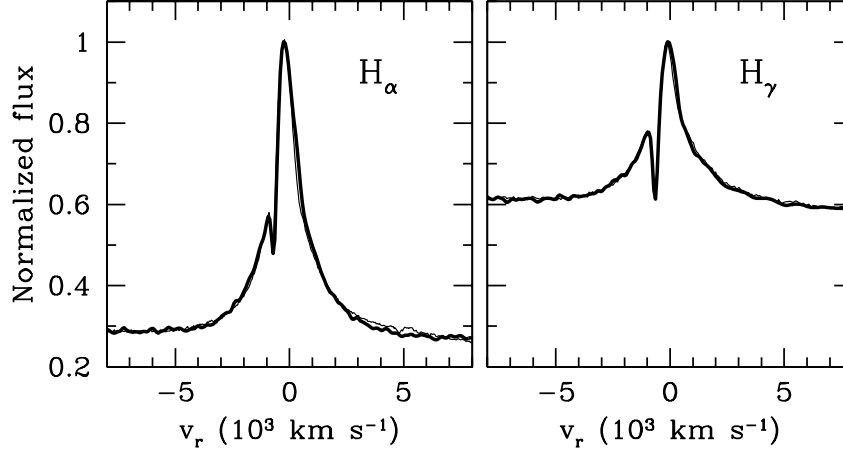


Figure 3: Model profiles of  $H\alpha$  and  $H\gamma$  (*thick* line) compared to the observed spectrum (Mauerhan et al. 2013). Small excess of the observed flux in the red wing of  $H\alpha$  at about  $5000 \text{ km s}^{-1}$  is caused by the presence of weak He I 6678 Å line.

## 5 Discussion and Conclusions

The goal of the paper was the answer to the question, whether the light curve and spectra of supernovae II<sub>n</sub>-P were consistent with the scenario B prompted by the idea of Dessart et al. (2009) that the spectrum of SN 1994W formed in the slowly expanding envelope ( $< 1000 \text{ km s}^{-1}$ ). In the thin shell approximation with radiative diffusion a simple model was developed to compute the luminosity and dynamics of SN 2011ht. The modelling demonstrates that the light curve and the low expansion velocity are consistent with the low energy explosion ( $\approx 6 \times 10^{49} \text{ erg}$ ) and ejected mass  $\leq 2 M_{\odot}$  occurred in the CS envelope with the radius of  $\sim 2 \times 10^{14} \text{ cm}$  and the mass of  $6 - 8 M_{\odot}$ . In this scenario a better agreement with the observed light curve is achieved, if one admits the shell fragmentation. The issue of instabilities that give rise to the fragmentation is beyond the scope of the present paper. It should be emphasised also that we cannot rule out that in the framework of the radiation hydrodynamics one will be able to reproduce all the observations without invoking fragmentation.

The scenario B of the low energy explosion applied to SN 2011ht notably differ from the scenario A proposed for SN 1994W (Chugai et al. 2004). Major differences of the new scenario from the old one are: (i) factor ten lower energy and, as a result, the lower expansion velocity ( $< 1000 \text{ km s}^{-1}$ ), (ii) factor ten smaller radius of the CS envelope, and last but not least (iii) the

line emitting region in the new scenario is the massive ( $\sim 8 M_{\odot}$ ) shell accelerated by supernova explosion, while in the old scenario it was the undisturbed CS envelope with the mass of  $\sim 0.5 M_{\odot}$ . The scenario B is favourable by two reasons. First, late time spectra ( $t > 120$  d) of SN IIn-P do not show high expansion velocities which is a serious problem for the scenario A. Second, the emission of hydrogen lines by the low velocity optically thick shell permits one to describe all the hydrogen lines as demonstrated by the modelling of the  $H\alpha$  and  $H\gamma$  lines. In contrast, in the scenario A the  $H\gamma$  and  $H\alpha$  lines cannot be reproduced simultaneously in the model of the emitting undisturbed CS envelope. The concept of the low energy explosion for SN IIn-P events has been proposed earlier by Smith (2013); he attributes this subclass along with the SN 1054 (Crab) to the electron-capture supernovae.

Remarkably, the scenario B admits an observational test. It is based on the prediction that at the early stage preceding the total acceleration of the CS envelope, i.e., at  $t < t_a \sim 20$  days, the radial velocities of line absorptions should be equal to the expansion velocity of the undisturbed CS envelope, while the core of hydrogen emission lines should be significantly narrower than at the later epoch ( $t > t_a$ ).

The genesis of SN IIn-P is an open issue. Sollerman et al. (1998) have mentioned two possibilities for SN 1994W: star with the initial mass from the range of  $8 - 10 M_{\odot}$  with a core collapsing to the neutron star, or massive star ( $M \geq 25 M_{\odot}$ ) leaving behind the black hole. Both scenarios account for the absence of large amount of ejected  $^{56}\text{Ni}$ . From the point of view of producing a close massive CS envelope the progenitor with the mass of  $\sim 10 M_{\odot}$  is preferred. Indeed, several years prior to the SN outburst the explosive flash of degenerate neon may result in the ejection of all the pre-SN envelope (Woosley et al. 2002); for the massive star  $> 25 M_{\odot}$  that heavy mass loss prior to the collapse is unlikely because the final nuclear burning occurs in non-degenerate fashion. In the case of  $\sim 10 M_{\odot}$  progenitor the CS envelope with the radius of  $2 \times 10^{14}$  cm forms by 3 yr prior to collapse provided the mass outflow velocity is  $20 \text{ km s}^{-1}$ . Notably, the low explosion energy of SN 2011ht ( $\sim 6 \times 10^{49}$  erg) is consistent with the prediction of neutrino mechanism for  $\approx 10 M_{\odot}$  progenitor (Kitauro et al. 2006). Yet, it is noteworthy, that the collapse of massive star ( $> 25 M_{\odot}$ ) also can produce weak explosion (Woosley et al. 2002).

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## References

- Alexander D. R., *Astrophys. J. Suppl.* **29**, 363 (1975)
- Chevalier R. A., *Astrophys. J.* **207**, 872 (1976).
- Chugai N. N. and Chevalier R. A., *Astrophys. J.* **641**, 1051 (2006).
- Chugai N. N., Blinnikov S. I., Cumming R. J. et al., *Mon. Not. R. Astron. Soc.* **352**, 1213 (2004).
- Chugai N. N., *Mon. Not. R. Astron. Soc.* **326**, 1448 (2001).
- Dessart L., Hillier D. J., Gezari S. et al.) *Mon. Not. R. Astron. Soc.* **394**, 21 (2009).
- Giuliani J. L., *Astrophys. J.* **256**, 624 (1982)
- Kankare E., Ergon M., Bufano F., et al., *Mon. Not. R. Astron. Soc.* **424**, 855 (2012).
- Kitaura F. S., H.-Th. Janka H.-Th., Hillebrandt W., *Astron. Astrophys.* **450**, 345 (2006).
- Mauerhan J. C., Smith N., Silverman J. M. et al., *Mon. Not. R. Astron. Soc.* **431**, 751 (2013).
- Pozzo M., Meikle W. P. S., Fassia A. et al., *Mon. Not. R. Astron. Soc.* **352**, 457 (2004).
- Roming P. W. A., Pritchard T. A., Prieto J. L. et al., *Astrophys. J.* **751**, 92 (2012).
- Smith N., *Mon. Not. R. Astron. Soc.* **434**, 102 (2013).
- Sollerman J., Cumming R., Lundqvist P., *Astrophys. J.* **493**, 933 (1998).
- Sunyaev R. A. and Titarchuk L. G., *Astron. Astrophys.* **29**, 1215 (1980).
- Utrobin V. P. and Chugai N. N., *Astron. Astrophys.* **575A**, 100 (2015).
- Vishniac E. T., *Astrophys. J.* **274**, 152 (1983)
- Woosley S. E., Heger A., Weaver T. A., *Rev. Mod. Phys.* **74**, 1015 (2002).